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Research paper

# Polyscape: A GIS mapping framework providing efficient and spatially explicit landscape-scale valuation of multiple ecosystem services

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## HIGHLIGHTS

- Develops framework exploring land management impacts on multiple ecosystem services.
- Designed for supporting decisions from sub-field scale to ca 1000 km$^2$ scale.
- Data deficiencies reduced and participation increased through local knowledge.
- Prioritises existing feature preservation and identifies opportunities for change.
- Highlights opportunities to increase synergies in service provision.

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## ABSTRACT

This paper introduces a GIS framework (Polyscape) designed to explore spatially explicit synergies and trade-offs amongst ecosystem services to support landscape management (from individual fields through to catchments of ca 10,000 km$^2$ scale). Algorithms are described and results presented from a case study application within an upland Welsh catchment (Pontbren). Polyscape currently includes algorithms to explore the impacts of land cover change on flood risk, habitat connectivity, erosion and associated sediment delivery to receptors, carbon sequestration and agricultural productivity. Algorithms to trade these single-criteria landscape valuations against each other are also provided, identifying where multiple service synergies exist or could be established. Changes in land management can be input to the tool and "traffic light" coded impact maps produced, allowing visualisation of the impact of different decisions. Polyscape hence offers a means for prioritising existing feature preservation and identifying opportunities for landscape change. The basic algorithms can be applied using widely available national scale digital elevation, land use and soil data. Enhanced output is possible where higher resolution data are available (e.g., LIDAR, detailed land use or soil surveys). Deficiencies in the data are reduced by incorporating local stakeholder knowledge (increasing stakeholder participation in the negotiation process).



## 1. Introduction

International research suggests that there is scope for significant improvements in the provision of regulating ecosystem services, such as carbon sequestration, water quality, flood alleviation and erosion reduction, through targeted land management (Morgan, 2005; O'Connell, Ewen, O'Donnell, & Quinn, 2007; Post & Kwon, 2000; Wade, Jackson, & Butterfield, 2008). The effectiveness with which regulating services can be delivered depends upon their role as part of an integrated catchment system (MEA, 2005). This requires policy to be implemented in a spatially explicit context,

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so that features located where they will have greater benefit for ecosystem services are valued more highly than those in locations where they will have less impact. Furthermore, adaptations in response to regulatory drivers must be considered across multiple sectors, as measures implemented by one (e.g., upgraded flood defences) may have implications for others (e.g., floodplain habitats and biodiversity) (Holman et al., 2005; Wilby, Beven, & Reynard, 2008).

Local stakeholders have often developed a detailed knowledge of local environmental features that when included provides important information to guide sustainable development (Beer, Ibrahim, & Sinclair, 2005). Ideally this local knowledge and livelihood requirements should be integrated to allow landscape level decisions to be more acceptable to landowners, and also incorporate cultural values and views (Vanclay, Prabhu, & Sinclair, 2006). With issues including those raised by climate change and increasing rural and urban land use intensification (Holman et al., 2005; Huntington, 2006), it is critical that tools to engage and foster participatory approaches to management are in place (Vanclay et al., 2006). Specifically, it is widely acknowledged that spatially explicit valuations of landscape services in forms that can inform land use and management are needed and still lacking (Dominati, Patterson, & Mackay, 2010; MEA, 2005; Nelson et al., 2009; Robinson & Lebron, 2010).

In response to this, a Geographical Information System (GIS) framework (Polyscape) has been developed to explore the spatially explicit trade-offs amongst ecosystem services inherent in land cover placement within landscapes. Polyscape was designed to work within the constraints of available data; i.e., the core algorithms are designed to work with national scale datasets such as digital elevation, land use data and soil data, although enhanced output can be generated where finer resolution data are available (e.g., LIDAR data, detailed surveys). Algorithms are also developed with the intent to make both methodological assumptions and data deficiencies transparent. Although complex model output can be integrated within the framework, part of the original driver for Polyscape development was a perceived need for simple, transparent tools of appropriate complexity given data limitations and knowledge gaps. We seek to provide visualisations and means of understanding the core assumptions and limitations of both data and algorithms in ways that are intuitive to stakeholders.

The framework acts as a screening tool to identify areas where scientific investigation might be valuably directed and/or where a lack of information exists, and allows flexibility and quick visualisation of the impact of different rural land management decisions on a variety of sustainability criteria.

Specifically, Polyscape is designed to facilitate:

1. spatially explicit policy implementation;
2. integration of policy implementation across sectors (e.g., water, biodiversity, agriculture and forestry);
3. participation (and learning) by many different stakeholder groups.

Importantly, it is designed not as a prescriptive decision making tool, but as a negotiation tool. Algorithms allow identification of ideas of where change might be beneficial – for example where installation of "structures" such as ponds or buffer strips might be considered optimal at a farm scale – but also allows users to trial their own plans and build in their own knowledge/restrictions. The framework aims to highlight areas with maximum potential for improvement, not to place value judgements on which methods (e.g., tillage change, land use change, hard engineering approaches) might be appropriate to realise such potential. Furthermore, the toolbox aims to identify areas of existing high value – e.g., particularly productive cropland, wetlands providing high biodiversity and flood alleviation benefits, carbon sinks – and flag these as worthy of being considered for protection.

Polyscape includes algorithms to explore the impacts of land management change on flood risk, erosion, habitat connectivity, carbon sequestration and agricultural productivity. These draw heavily on recent research outputs and insights gained from work on impacts of land management change on flood risk (Carroll, Bird, Emmett, Reynolds, & Sinclair, 2004; Jackson et al., 2008; Marshall et al., 2009), erosion (Henshaw, 2009), agri-forestry work (Beer et al., 2005), habitat connectivity (Eycott, Watts, Moseley, & Ray, 2007) and work on interactions between community and natural resources at the landscape scale (Vanclay et al., 2006). Changes in land management can be input to the tool and "traffic light" coded impact maps produced in seconds to minutes, allowing flexibility and quick visualisation of the impact of different decisions. Interactive capabilities to facilitate stakeholder engagement and to allow local requirements and knowledge to be easily incorporated in decision making are also included.

Polyscape has a number of unique features and capabilities not contained in any other ecosystem service support framework in current circulation; some alternative and/or complementary approaches exist or are being created as development targets of a number of ongoing research programmes (e.g., Lane, Reaney, & Heathwaite, 2009; Tallis et al., 2011; Van Delden et al., 2010). We discuss these in Section 2.8 (after the component models of Polyscape have been described) so their alternate and complementary natures can be fully appreciated.

The next section (Section 2) contains descriptions of the individual valuation algorithms and finishes with a discussion of alternative approaches. Section 3 contains example Polyscape output from a case study site (the Pontbren catchment in Wales, UK). We conclude with a discussion of the utility of the framework in this catchment and identify priority directions for future research.

## 2. Algorithm/tool descriptions

A fundamental input to Polyscape is a raster of elevation values, from here on called a Digital Elevation Model (DEM). All algorithm calculations and valuations are produced at the resolution of this DEM – this ensures each service valuation delineates the landscape into elements consistent (identical) with the other service valuations so trade-offs can be meaningfully calculated. Applications to date suggest that a 5 m by 5 m DEM provides more than sufficient resolution for making decisions at the field scale. The extent to which utility decreases as resolution degrades is still to be established, but applications using 10 m by 10 m and 20 m by 20 m DEMS have to date provided generally appropriate information. For example, ground-truthing by owners has showed topographical routing and identification of various landscape features (e.g., boggy patches, erosion-prone slopes, and productive land) to be appropriate.

Polyscape is not designed to be prescriptive; algorithms can be modified by the user or combined with the user's own applications. Of the eight tools used in Polyscape applications to date, five consider both current and potential impacts of land management change on single service criteria. These are (1) habitat networks; (2) flooding; (3) erosion/sediment delivery; (4) carbon sequestration and (5) agricultural productivity. Each classifies elements (i.e., each grid of elevation data) within the landscape into one of five categories; very high existing value, high existing value, marginal value, opportunity for change or high opportunity for change. These classifications are visualised using a five-way colour system. The default palette uses a traffic light system; red colours suggest that stakeholders "STOP and think carefully before making any changes to the landscape at these locations", yellow means "proceed with caution", and green colours indicate a "green light to proceed with

modifying the landscape". This can be altered if required by the user (for example, for forms of colour blindness). We purposely restrict output to five colours to facilitate visualisation and negotiation. The sixth tool calculates trade-offs and co-benefits between these five ecosystem services, and the seventh provides pre-processing algorithms. These can be used to ensure topographic consistency between river networks and elevation information. The eighth tool provides editing capabilities to allow stakeholders to update and/or correct flaws in data and to enter their own requirements.

### 2.1. Habitat augmentation/protection tool

A central problem in ecology and conservation biology is the habitat loss and fragmentation induced by anthropogenic activities (Benton, Vickery, & Wilson, 2003). It is generally accepted that landscape connectivity, often defined as the ease with which members of a population of interest can move about within the landscape (Kindlmann & Burel, 2008; Merriam, 1984), plays an essential role in the dispersal of organisms among habitat patches and thus the conservation of biodiversity (Tischendorf & Fahrig, 2000). Species are likely to survive only within networks of patches that are sufficiently connected by dispersing individuals (Lin, 2009).

Various metrics have been used for the purpose of measuring connectivity. Methods based on distance are common, ranging from simple nearest neighbour metrics examining only the cost of crossing hostile terrain to more complex ones taking into account occurrence of multiple habitat "patches", patch size, shape, etc. (Kindlmann & Burel, 2008). Such methods generally use a cost-distance approach, where the cost of crossing a non-habitat landscape element is a function of the Euclidean distance across the element and a measure of permeability: the more hostile, the less permeable the terrain will be. Assigning different permeabilities to different types of hostile terrain, land cover, etc. allows varying mortality risks, different movement patterns, and boundary crossing to be implicitly taken into account. Parameterisation of the permeability values in cost-distance modelling is challenging; this is usually defined on the basis of expert advice (Janin et al., 2009).

The habitat layer follows the calculation procedure recommended by UK Forest Research (Eycott et al., 2007), a cost-distance approach considering maximum estimated dispersal distances between patches of habitat above a user-specified area. It first calculates cost-distances for organisms crossing through hostile terrains from each habitat patch, with individual landcover types having specified permeabilities for the organism of interest. Permeability parameterisations provided with Polyscape are from the Eycott et al. (2007) procedures and are based on studies from a selection of key species in Wales and the land use regimes in proximity to those species. However, users have the option to input their own permeability values and so can tailor the tool to the needs of their own regions. As input, the habitat tool requires the digital elevation model, spatial coverage of each habitat of interest the species of interest, the cut-off "cost" at which dispersal across hostile terrain is considered zero or insignificant, and the minimum area of habitat patch needed for a patch to be considered of value.

It is important to note that multiple (and potentially conflicting) habitat valuation layers can be produced for one site, depending on how many species and/or habitats of interest are under consideration. The current version of Polyscape assumes reducing fragmentation for high value habitat is preferable, although a later version will also include consideration of habitats where fragmentation is valuable (e.g., when attempting to protect habitats and/or particular flora or fauna within them by isolating them from other habitats and predatory flora/fauna).

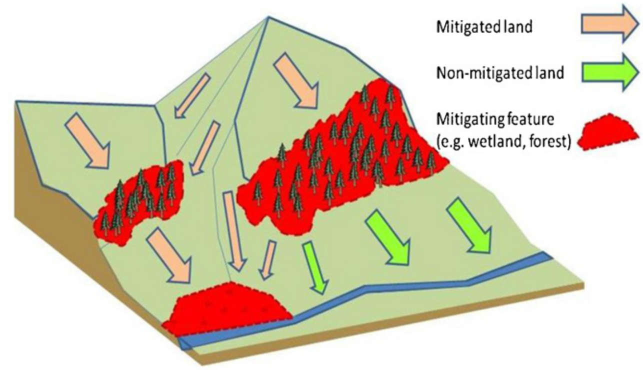


**Fig. 1.** Delineation of landscape into flood mitigating, mitigated and non-mitigated areas.

### 2.2. Flood mitigation tool

Areas of land with high storage and/or high infiltration capacity have the capacity to mitigate floods by acting as a sink for fast moving overland flow and near-surface subsurface flow; either storing this water or routing it more slowly through subsurface routes. The function of such elements within the landscape on runoff changes depending on their spatial placement; those with negligible "uphill" contributing area have far less impact than those receiving contributions from substantial low-permeability areas (Jackson et al., 2008). The flood mitigation tool hence takes information on the storage and permeability capacity of elements within the landscape from soil and land use data. Using a novel algorithm based on modifying flow accumulation according to permeability and storage, it discretises units within the landscape according to similarity of their hydraulic properties and spatially explicit topographical routing.

In its simplest form, ignoring temporal effects, the flood mitigation algorithm corrects flow accumulation by removing any flow that accumulates on these "sink" areas. These areas are then considered to be of low priority for flood risk (mitigation already exists). This topographically explicit categorisation of the landscape is demonstrated in Fig. 1. All land use or soil types that provide mitigation are treated as of high existing value, and areas that are intercepted by these features are considered to be mitigated. Areas where a large amount of unmitigated flow routes directly to waterways are treated as priority areas for change. Parameters to define thresholds for the "corrected" flow accumulation values are used to categorise priority areas for targeting change, with default parameters provided.

As input, this form requires stream network data, a hydrologically consistent digital elevation model (consistent with the stream network and with local depressions removed) and land use data. Soil data is an optional input; this should always be included in regions where it is available (unless known to be of insufficient quality); if not available (as has been our experience in data sparse regions) a benchmark soil hydraulic capacity is input and spatial variations in this are estimated through applying multipliers to the land use through specification of hydraulic capacity multipliers (e.g., Chandler & Chappell, 2008). A pre-processing tool is included with Polyscape to generate a hydrologically consistent DEM from a "standard" DEM (see Section 2.7 for further details).

A more sophisticated version of the algorithm can be applied to value land under different rainfall events (e.g., design flood rainfall input, known return period rainfall events) and antecedent conditions, cascading water through hydrological response units discretized in the landscape using a "fill and spill" approach. This

requires more data (or assumptions) on soil water holding capacities and hydraulic conductivity and is the subject of a separate paper in preparation.

### 2.3. Erosion/sediment delivery risk tool

Soil erosion can severely reduce the productivity of agricultural land (Lal, 2001) and is estimated to be responsible for economic losses of approximately £700 million per year in England and Wales alone (Evans, 1996). Furthermore, it is increasingly recognised that the delivery of eroded sediment to watercourses can represent an even greater problem (Walling & Collins, 2005). Elevated rates of sediment supply can reduce the conveyance capacity of river channels, thus increasing flood risk and restricting navigation; pose a risk to public water supplies; threaten important aquatic habitats such as fish spawning gravels; and facilitate the transfer of nutrients (e.g., phosphorus) and contaminants (e.g., pathogens, metals, radionuclides, and pesticides) that can reduce water quality (Walling & Collins, 2005).

The most severe forms of soil erosion tend to occur in areas where overland flow coalesces in natural topographic depressions, generating sufficient kinetic energy to detach and mobilise soil particles. This lowers the soil surface, promoting further flow concentration and, ultimately, the establishment of erosional channels (rills and gullies) (Morgan, 2005). Areas of land that are vulnerable to this type of erosion are identified in Polyscape using the Compound Topographic Index (CTI) (Thorne, Zevenbergen, Grissenger, & Murphey, 1986). The CTI represents the erosive potential of overland flow by combining three important factors in this form of soil erosion: overland flow magnitude, slope, and overland flow concentration (Zevenbergen, 1989). It can be considered similar to specific (width-averaged) stream power: a parameter successfully used to represent flow intensity and sediment transport potential in rivers (Bagnold, 1966).

CTI (m) is defined as $CTI = A \times S \times PLANC$, where $A$ = upslope drainage area ($m^2$) (after “sink” areas have been accounted for – see Section 2.2); $S$ = local slope (m/m); and $PLANC$ = planform curvature (1/100 m). $A$ acts as a surrogate for overland flow magnitude as the two variables are generally positively correlated. $PLANC$ is a measure of landscape convergence (negative for spurs, positive for swales) which indicates the degree of overland flow concentration. A full derivation of $PLANC$ is not presented here due to space limitations but can be found in Zevenbergen and Thorne (1987).

In addition to the topographic controls represented by the CTI, the probability of soil erosion occurring at a particular location is also dependent on factors such as soil and vegetation characteristics (Morgan, 2005). These influences are represented in Polyscape through the use of user-defined critical, or threshold, CTI values. These can be empirically defined for a particular region, soil type, crop combination, etc., on the basis of local knowledge, field observations or aerial photography (cf. Thorne & Zevenbergen, 1990), or through the use of values derived for comparable sites (e.g., Parker, Bingner, Thorne, & Wells, 2010).

The subsequent transfer of eroded sediment to rivers and streams relies on the existence of hydrological connectivity between the point of origin and the watercourse (cf. Lane et al., 2009). Areas of land which are vulnerable to severe soil erosion *and* at risk of being linked to proximate watercourses by uninterrupted overland flow are identified in Polyscape by combining the CTI layer with the flood mitigation tool discussed in Section 2.2. This allows users to identify and prioritise areas of land for sediment delivery mitigation efforts (e.g., buffer zone creation; Muscutt, Harris, Bailey, & Davies, 1993).

### 2.4. Carbon sequestration tool

The global sum of carbon in terrestrial biomass and soils is approximately three times greater than the carbon dioxide ($CO_2$) in the atmosphere (Falkowski et al., 2000), and exchange between soil organic carbon and atmospheric $CO_2$ is one of the largest fluxes in the carbon cycle. Land use change or conversion to cropping and agricultural farming has led to historic losses of soil carbon (FAO, 2001) and increased emissions of $CO_2$. The potential to reverse this trend, increasing soil carbon and hence reducing green house gases, has been realised by many (Lal, 1999; Post & Kwon, 2000; Schlesinger, 1984; Trumbore, 1997). Climate change and its associated impacts are not the only drivers for increased soil carbon sequestration; other environmental and socioeconomic realms can also benefit from increased carbon within the subsurface. Co-benefits for other services/risk mitigation include: (a) increased water holding capacity and infiltration capacity; leading to (b) flood and drought alleviation benefits; (c) increased structural stability; which combined with (a) results in (d) reduced erosion; (e) increased crop yields and plant biomass; (f) increasing nutrient reserves and (g) enhanced biodiversity in soil ecosystems.

Many international commercial, non-governmental and governmental endeavours are implementing programmes to increase carbon sequestration through tree planting and other “carbon credit” schemes. With the many ecological co-benefits of increasing carbon sequestration in soils, the rationale for seeking opportunities to spatially optimise such carbon sequestration-led changes to enhance other environmental services is obvious. Much of the current effort in carbon sequestration focuses on increasing sequestration in depleted areas. However, this can be a long, slow process with turnover varying from 14 years to 400 years depending on the type of ecosystem (Raich & Schlesinger, 1992). Similarly, if land that is being employed to sequester carbon undergoes a degrading change, the negative effects of this can last decades to centuries. Focus and research in carbon stocks and flows should therefore include identifying areas in the landscape that already have substantial carbon within the subsurface and protection of these areas, potentially preventing carbon losses as a result of factors such as erosion. The Polyscape carbon layer seeks to identify specific areas of the landscape that are prone to carbon losses and could be protected, as well as those that have potential to be modified to store additional carbon.

Carbon opportunity calculations are based on the IPCC tier 1 protocols (IPCC, 2006); separating carbon into above ground biomass, below ground biomass, deadwood, litter, and soil carbon. Two differing and complementary valuations are provided. The first calculates carbon levels at pseudo-steady state; assuming that the land use/management regime has been in place long enough for the carbon fluxes to be at equilibrium. The second identifies where the current management regime is likely to be either significantly decreasing or augmenting stocks of carbon left by previous regimes – correlating to probable emissions or sequestration of $CO_2$ respectively. For example, many woodland areas have moderate to high carbon stocks and hence are considered as of moderate to high value according to the first “pseudo-steady-state” calculation, indicating preservation is desirable. Despite this high valuation relative to other land management regimes, if the woodland has been planted onto peat, for example, a reduction in stored carbon (and associated net $CO_2$ emission) might be anticipated and interventions to prevent this/revert land use might be appropriate. Therefore the second valuation layer examines the expected carbon stock at equilibrium versus the current carbon stock, considering both rooting depth and organic matter concentration. For each landscape unit, if the carbon stock per unit area is expected to reduce, an opportunity to reverse this is flagged. Conversely, if the carbon stock is expected to increase, protection is suggested. If

carbon stocks are expected to remain static, Polyscape will indicate preservation of the carbon stock "status quo".

Appropriate "threshold" values for identifying opportunities for additional sequestration and/or areas for preservation will change according to region. The amount of carbon sequestration and $CO_2$ emission varies according not only to land use but also to the underlying geology and climatic influences (temperature, rainfall, etc.) (Lal, 1999). Default carbon valuation classifications are therefore data set-specific and an option also allows the default to be regionally specific (for example, nutrient-poor soils might still be considered of high value in a "low" fertility region). This "regional" estimate of thresholds is calculated by looking at the means and standard deviation of carbon stock in the region of interest. This allows either an "absolute" valuation according to national or international standards to be made, or a "relative" valuation according to the mean and ranges of carbon sequestration in the area of interest. As always, the user is able to vary these default classification ranges as perceived to be appropriate.

### *2.5. Agricultural valuation tool*

The agricultural valuation tool provides a screening method to categorise land by its productivity value for farmers. This can be useful for the stakeholders themselves, in highlighting areas which might be over or under utilised. However, stakeholders in small to medium farming operations with livelihoods dependent on the land generally possess a detailed understanding of this land, so its value can sometimes be limited for this purpose. Irrespective of this, the agricultural valuation tool serves an important purpose when it comes to considering trade-offs and synergies between services. Options can be explored to protect high productivity land and to focus changes on marginal or non-productive land. Where this is not possible, the provision of appropriate compensation (i.e., compensation respecting the high value of land being taken out of production) can be considered.

The agricultural valuation tool is based on simple rules examining slope, aspect, water regime (e.g., whether the soil is free draining, prone to waterlogging, etc.) and soil fertility. Additionally the current land use regime is considered in order to examine the degree to which this value is currently utilised. A food security layer is also calculated. These rules were developed in consultation with farmers and other rural industries (e.g., tractor manufacturers) in temperate upland regions, and have performed very well in applications to date. However, the rules would need modification if taken to more extreme climatic areas (e.g., arid) or topographic regions (e.g., highly mountainous, flat, or terraced).

In the calculation of perceived agricultural value, i.e., the value of the land independent of its current land management utilisation, each element in the landscape is categorised as one of: very high value, high value, marginal, low value, or no value according to (a) slope, (b) soil drainage characteristics and (c) fertility information (if available). Users can also choose to consider aspect (varying according to hemisphere and with zero effect near the equator); this is used to upweight soil drainage and fertility valuations. For example, in the northern hemisphere south facing land catches light and tends to have better natural drainage and fertility characteristics than the "same" soil type in a non-north facing location.

Layers are generated with these individual valuations, corrected for aspect or not as appropriate, and combined to give an "overall" valuation. The user can choose to include or exclude any of these categorisations in the final valuation, in which case the "worst value" of the included categorisations is preserved. It should be noted that this valuation layer ignores existing land use (except implicitly, insofar as land use may have modified soil characteristics, etc.); it is an indication of potential rather than current value.

Further valuation layers consider the current utilisation of the land. A "current" valuation layer considers only whether the current utilisation is of high or low agricultural value; for example arable land is given a high valuation, improved grassland a moderately high valuation, bogs and woodland are considered of no agricultural value. There is an option to instead calculate a similar layer that is broader in its definition of valuable if local food security is of importance; for example broadleaved woodland and open water are considered to have some marginal value from a food security perspective due to hunting and fishing potential.

Two agricultural security layers compare the current agricultural utilisation of land with its "potential" productivity and highlight where land appears to be over or under utilised. For example, a steep sloped, low fertility area that is under intensive cropping is identified as over-utilised and potentially an area where change might be appropriate. Similarly, flat, well-drained and fertile land under plantation forestry or shrubland is considered to be under-utilised. The two layers differ only in the resolution of the productivity classes; one has five classes while the second has three. The first contains more information but can be harder to interpret while the second in our experience so far provides a more appropriate vehicle for a "first look" to target change and identify areas to protect.

Inputs are a DEM, soil information, land use information and two or more critical slope values (1st is the cut-off for very productive land, 2nd is the cut-off for moderately productive land). The DEM should be the original data, *not* the hydrologically corrected version which introduces artefacts in slope. By default a value of $5^\circ$ is used as the maximum threshold for valuable land, $15^\circ$ as the maximum to define marginal land and values greater than this to identify non-valuable land; however, the user can specify other slope threshold values. Note appropriate threshold values will change according to region (as in the case of the carbon sequestration tool) and according to quality/resolution of the DEM. Soil drainage and fertility productivity classifications are dataset-specific and can also be regionally specific (for example, nutrient-poor soils might still be considered of high value in a "low" fertility region). Default parameterisations are provided for national data in the UK (National Soil Resources Institute) and in NZ (NZ Land Resource Inventory), and the user is able to adjust these as required. For other regions, users can input tables with their own classifications of soils and then run the tool.

### *2.6. Trade-off tools*

Polyscape includes algorithms to trade the individual ecosystem services, represented by the GIS layers, against each other in a number of ways. These allow identification of areas where interventions provide multiple benefits and areas where intervention is clearly undesirable because existing socioeconomic or ecological value is high. Potentially, there are an almost infinite number of options for numerical evaluation of trade-offs. Four are included in the current version of Polyscape. These include an additive option (which treats all services equally), a weighted additive (which allows the addition of weightings for individual services), a conservative option (which only identifies areas where positive synergies exist) and a Boolean option (which enables users to select a combination of additive and conservative options for each service). It is possible to produce two way, three way or even four way trade-off layers in Polyscape. These trade-off maps offer a means for recognising the value of existing landscape features and targeting and prioritising opportunities for landscape change by being explicit about where trade-offs and synergies between these services occur within the landscape.

As an example of the trade-off options possible, where two service layers are being traded against each other using the additive option, the trade-off layer categorises each element as one of:

(a) *synergistic opportunity for change* (highly beneficial impacts could occur from appropriate change in both service categories);
(b) *positive impact of change* represented by dark green (one service will be positively impacted by change while the other is neutral);
(c) *trade-off or negligible impact from change* represented by amber (change is likely to either be neutral in both services or positive in one while negative in the other);
(d) *negative impact of change* represented by dark red (one service negatively impacted by change while the other is neutral); most forms of change would not recommended;
(e) *synergistic benefits in current land use* represented by bright red; change is likely to degrade both services and high consideration should be given to protecting the status quo.

When three services are being traded off against each other using the additive option, category (a) or bright green implies appropriate change would be positive in at least two services and at worst neutral in the other; (b) at least 1 positive and no negatives; (c) trade-offs or neutral benefits in all; (d) change providing no benefits and worsening provision of at least one services and (e) worsening of two or more provisions.

We have deliberately chosen this simple classification system rather than implementing economic assessments (e.g., Nelson et al., 2009; Van Delden et al., 2010) or more complex multi-criteria decision analysis methodologies (e.g., Pietersen, 2006; Romero & Rehman, 2003). Such assessment methodologies require assumptions that can be difficult to communicate and arguably reduce transparency. At a later stage we envisage augmenting our classification system with options for economic assessment, and evaluation of ecosystem services via the soil natural capital concept proposed by Robinson, Lebron, and Vereecken (2009) and Robinson and Lebron (2010) – an approach examining stocks and fluxes of energy and mass to provide objective, less human-centric valuations of services.

### 2.7. Pre-processing and editing tools

The pre-processing tool facilitates creation of a hydrologically consistent DEM from a "standard" DEM, generate a raster containing stream information in the format required for operation of the flood mitigation algorithm, and create a "hillshade" (a shaded, visually intuitive elevation relief raster) and stream vector data in suitable format to enhance display/visualisation of the output layers from the previously described tools. The hydrologically consistent DEM is generated by first filling sinks in the DEM and then either (a) generating a stream network from the DEM if no independent information on the stream routing network is available or (b) "burning in" the stream network to the DEM using the established "Agree" method (Maidment, 2002) if an independent stream network layer is present.

Inputs are the DEM and *either* a stream network layer or the threshold (in hectares) above which flow accumulation is assumed to result in stream formation. The default value provided is 8 ha but the appropriate value for a particular case could vary significantly according to geomorphic characteristics of the landscape of interest (see Montgomery and Dietrich (1992) for discussion of appropriate values).

The editing tool allows the user to update land use data, soil data, or stream network/drainage data. This allows local stakeholder knowledge to be incorporated into the decision making process reducing the errors caused by outdated, coarse-scale, or otherwise erroneous national scale data. It also allows users to mark off specific areas (e.g., a field of cultural or other social significance or a nationally protected site) as either taboo – unchangeable – or restricted in change.

### 2.8. Alternative and complementary approaches to landscape-scale valuation

The utility of any multi-criteria decision support tool is in part a function of its component models. We have presented the current component models used in Polyscape applications to date, and discussed the need to refine and augment these for wide-scale applicability in varying hydro-climatic and geomorphic environments, and for suitability under differing levels of data support. There is a wide variety of site-specific multi-service ecosystem valuation applications in the literature, with components designed for some of the services represented in Polyscape along with others (e.g., Britz et al., 2010; Rutledge et al., 2008; Sieber et al., 2008; Van Delden et al., 2010; Woods et al., 2006). Most would require substantial modification to become more generically applicable, but could be easily transferable where data support and hydro-climatic and geomorphic regimes are similar to those for which the model was designed. The choice of models and "success" of the various applications also hold a variety of lessons that may inform collation of suitable libraries of models for generic (widely applicable) tools.

Our literature searches for similar landscape decision support tools suggest that the most comparable generic tool currently available is the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) tool described in Nelson et al. (2009) and Tallis et al. (2011). Like Polyscape, it is designed to inform decisions about natural resource management (although InVEST is of broader scope, in that it also considers marine areas while Polyscape is primarily concerned with rural land management in terrestrial environments). The InVEST tool is the result of a large (and ongoing) programme of work called the Natural Capital Project, led by Stanford University, the Nature Conservancy, and World Wildlife Fund. InVEST currently considers water quality, soil conservation, carbon sequestration, biodiversity conservation, aesthetic quality, coastal and marine environment vulnerability, hydropower production, pollination services and values of selected market commodities. It has so far been applied at slightly larger scales and coarser resolution than Polyscape is designed for; and in keeping with this, some of its algorithms appear to be more applicable at the regional rather than the field scale considered by our tools. Others are less scale-dependent but with different strengths and weaknesses (for example InVEST's carbon valuation layer is near-identical to Polyscape's "pseudo-steady-state" valuation, and includes an economic valuation that Polyscape lacks, but does not include consideration of carbon fluxes/emissions). Both similarities and dissimilarities are encouraging: similarities from independent development may suggest scientific and practical consensus across disparate scales and regions; and dissimilarities may provide opportunities to investigate scale and regional differences and move towards regionalizable, scalable approaches.

Along with InVesT and Polyscape, two other modelling platforms are worthy of note due to their holistic approach to multiple ecosystem services. These are the Artificial Intelligence for Ecosystem Services (ARIES) tool (Bagstad, Villa, Johnson, & Boigt, 2011) and Envision (Bolte, Hulse, Gregory, & Smith, 2007; Hulse, Gregory, & Smith, 2008; note the name Envision was given to the approach described in these after publication). They are both designed to be extremely flexible in the spatial and temporal scales as well as types and number of ecosystem services considered, and hence can be considered to span both the local scale considered by Polyscape

and the regional scale considered by InVest. However, in other ways the design philosophies of the latter are very different. Although both frameworks are generic and capable of including a variety of model types, they currently rely heavily on empirical approaches to extract relationships between inputs and outputs, using neural networks/Bayesian statistical approaches (ARIES) and principal component analysis (Envision) along with agent based modelling (both). Although these approaches are capable of extracting significant relationships that may have been unidentified by stakeholders and scientists to date, they are very data intensive and significant applications in data-rich sites will be needed before they are suitable for data-scarce sites. Polyscape is designed to cater for data scarce environments, and where possible takes a process driven rather than data driven approach to modelling. As with InVest, it can be expected that as the respective toolboxes continue to develop there will be opportunities for each to learn from each other.

A further interesting framework and suite of models is being developed within the Multiscale Integrated Earth Systems project (MIMES), the objectives of which are discussed within Boumans and Costanza (2007). MIMES is designed to advance the study of ecosystem services for use in integrated assessment, and builds on the GUMBO model (Boumans et al., 2002), a global unified metamodel of the biosphere simulating the integrated earth system (water and nutrient fluxes) while also modelling social and economic dynamics. It is difficult to evaluate it against the other ecosystem evaluation frameworks until publications from the various collaborators in the MIMES project enter the public domain, which is expected to happen in the near future.

More generally, van Delden, van Vliet, Rutledge, and Kirkby (2011) provide a very recent review of current approaches and discuss the various issues surrounding development of integrated models (linking land use models with bio-physical processes and socioeconomic considerations). These include scale, data scarcity, computational constraints, and of course methodological and philosophical approaches to balancing conflicts between users, science, and data. One of the defining aspects of Polyscape comes in its approach to this balance of conflicts – we acknowledge data scarcity and computational constraints, and user knowledge is explicitly sought to overcome data constraints where possible. We also seek to use and communicate the most robust available scientific knowledge given these constraints.

A second defining aspect of Polyscape is the simple classification system used to identify and communicate synergies, trade-offs, opportunities and identification of where protection may be beneficial. This is in stark contrast to the more standard (and more complicated) economic assessment approaches (e.g., Nelson et al., 2009; Van Delden et al., 2010) or multi-criteria decision analysis methodologies (e.g., Pietersen, 2006; Romero & Rehman, 2003) prevalent in the literature. Such assessment methodologies have an important role to play but introduce additional layers of complexity and require assumptions that can be difficult to communicate. Our simple approach is designed for transparency of communication and to force stakeholders rather than modellers to balance the respective values of differing ecosystem services.

Polyscape is further differentiated by its scale. It is specifically designed for application at a local scale, in contrast to the other generic ecosystem valuation tools – to examine impacts of small-scale (sub-field level) changes at landscape scale. It is also designed to operate as rapidly as possible when being applied in the field; scenarios can be input and output then produced in seconds to minutes for individual services. This allows the effect of proposed interventions to be immediately evaluated.

In addition to tools specifically designed to consider multiple ecosystem service provision, a more specifically targeted tool also shares characteristics with Polyscape both in terms of design philosophy and its “spatially explicit” nature at the field scale. SCIMAP is a joint project between Durham University and Lancaster University in the UK, developing a framework for the analysis of the relative risk of diffuse pollution from different locations within the catchment affecting receiving water bodies (Lane et al., 2009). The project specifically focuses on hydrologically connected and “risky” land uses to determine priorities for management activities, and on determining where efforts should be concentrated in order to achieve environmental protection. It works at a 5 m by 5 m resolution (comparable to the suggested 5–10 m resolution suggested for Polyscape), working out the relative risk of each location in the landscape being connected to a river, lake or groundwater and “routing connected risk across the landscape, accumulating it along flow paths”. Its similarities are particularly interesting given its similar design philosophy – the perceived need for practical tools for landscape management working within knowledge and data limitations.

## 3. Case study application

Our case study site is the 12.5 km$^2$ catchment of the Pontbren in mid-Wales (Fig. 2a). Land cover consists mainly of ‘improved’ pasture, semi-natural, unmanaged moorland, mature woodland, recent tree plantations, and small paved/roofed areas, root crops and open water (Fig. 2b). Agricultural soils in the catchment have a high clay content and are generally relatively impermeable, with the less intensively farmed areas in the upper catchment (moorland) having higher organic matter contents (Fig. 2c). Elevation in the catchment ranges between 170 m and 425 m (reference to sea-level). Its topographical variation is pictorially represented in the hillshade shown in Fig. 2d. More detail on the physical characteristics of the catchment can be found in Marshall et al. (2009).

Approximately half of the catchment is farmed by the “Pontbren group”, a consortium of ten contiguous farms exploring opportunities to establish sustainable farming practices. The farmers began a major programme of shelterbelt and hedgerow planting in 2001. In addition to shelter provision the farmers were also interested in other potential benefits of increased tree cover, including biodiversity conservation and flood mitigation. Observations made by the farmers of increases in soil infiltration adjacent to newly planted hedgerows, and the question of whether such local scale interventions could have a significant dampening effect on flood peaks, led to a wide range of research activity including studies on shelter belt infiltration capacities (Bird et al., 2003; Carroll et al., 2004), catchment-wide hydrological monitoring and modelling (Jackson et al., 2008; Marshall et al., 2009; McIntyre & Marshall, 2010), geomorphologic processes (Henshaw, 2009), biodiversity benefits (Moro & Gadal, 2007) and water quality (Reynolds et al., 2010) being conducted at Pontbren. We use data from this site to provide output to demonstrate and explain the functionality of the individual Polyscape tools described in Section 2 of this paper. Space constraints do not permit us to go into detail of the engagement process with stakeholders and outcomes from this; however such detail is provided in Pagella (2011).

### 3.1. Habitat connectivity layer

To demonstrate the habitat connectivity algorithm, we focus on broadleaved woodland, a key habitat in Wales. This covered approximately 3.1% of the Pontbren catchment in 1990 (the approximate year in which data in the area was collected for a national survey). Areas where planting additional broadleaved woodland is considered to be high priority in terms of habitat creation are those where cost-distance calculations suggest “focal” (i.e., indicator) woodland species could reasonably disperse to. Hence creating habitat for these species would extend corridors for movement

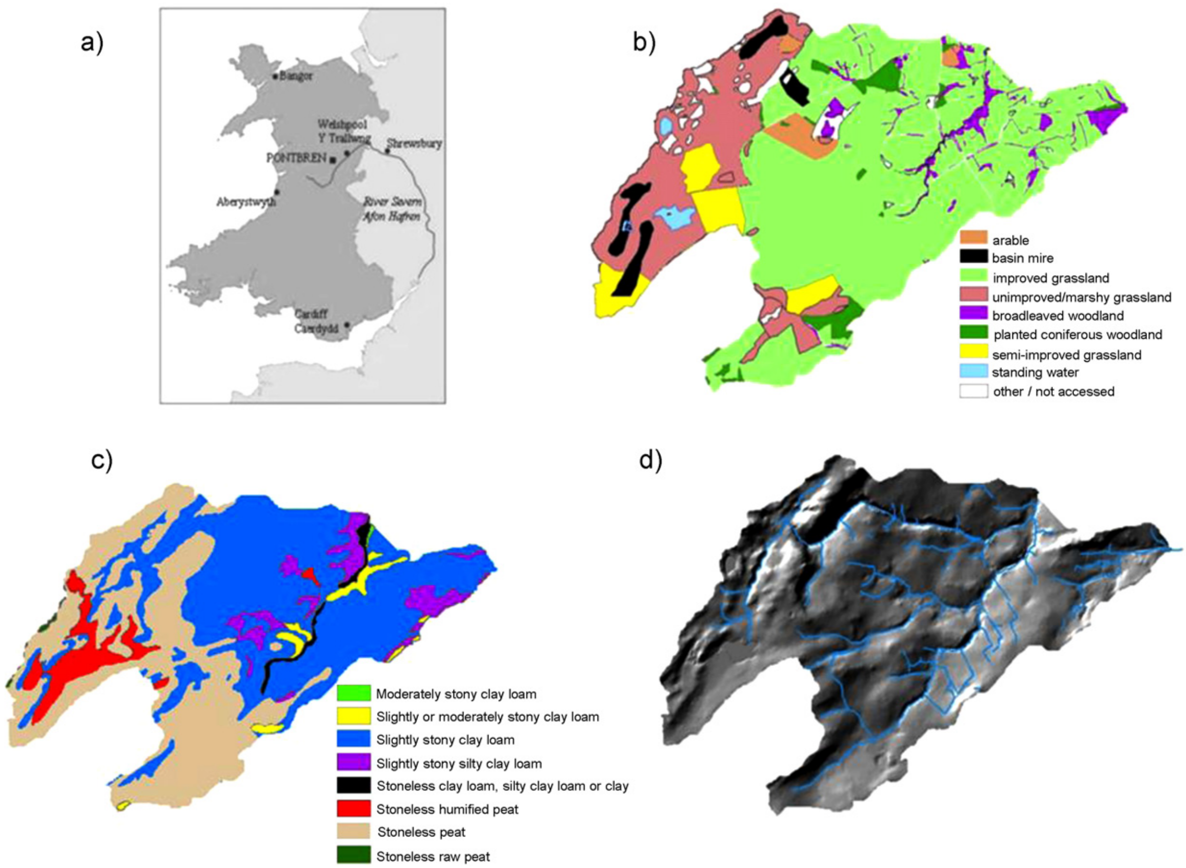


**Fig. 2.** (a) The Pontbren location in mid Wales, (b) the land use data used in this application, (c) the soil map and (d) the hillshade of catchment topography with stream network generated from the DEM to aid visualisation of output.

of species, and enhance survival chance. In this application, we assume that broadleaved woodland habitat above 2.5 ha in area is significant.

Fig. 3a and b shows the habitat augmentation layer for Pontbren for two "scenarios". The first uses the original national scale vegetation data from 1990 (Fig. 3a) and the second a version of this data updated to include the effect of the planting and pond creation carried out by the farmers between 2001 and 2007 (Fig. 3b). Broadleaved woodland habitat is highlighted in bright red as key for protection. Other important habitats are represented in dark red (note that as is the colour is superimposed over a hillshade, this appears to many eyes as a purplish-brown). Unlike other layers, dark red does not indicate areas of lower priority for change than those displayed in bright red, rather it distinguishes the habitat under current examination from other important habitats to facilitate visualisation and interpretation of the maps.

This demonstrates the change in valuation of habitat connectivity services before and after the tree-planting initiative of the Pontbren farmers. As Table 1 shows, the percentage of the Pontbren landscape covered by key woodland habitat increased from 3.1% to 9.9%, and an additional 21.7% of the catchment became reachable by focal species for this habitat, hence providing a much less fragmented landscape for species that prefer woodland habitat.

### 3.2. Flood mitigation layer

Fig. 3c and d shows the flood mitigation layer for Pontbren, using the two land use scenarios described in the previous section. High priority areas for tree planting are those where unmitigated flood generating land concentrates flow accumulation. High flow concentration spots (grassland with > 500 m$^2$ non-mitigated contributing area) are shown in light green, moderate flow concentration spots (125–500 m$^2$) are shown in dark green, areas with negligible flow (<125 m$^2$ contribution) are shown as orange and areas that are providing mitigation of flow (e.g., trees, ponds, deep permeable soils or other flow sinks) are shown as red.

Again, comparison demonstrates the changes in landscape valuation that occur as a result of varying land use. Visually, it is obvious that the additional planting has provided mitigation to a substantial additional area of the catchment, with areas of green much reduced. A quantitative summary of impacts is presented in Table 2. The tree planting so far undertaken by the farmers added approximately 3.2% of flood mitigating land to the Pontbren catchment but additionally provided mitigation to another 8.8% of flood generating land. A combined total of 12.0% of the catchment thereby gained protection even though the trees were planted primarily to provide shelter for livestock rather than for flood mitigation.

Optimal feature placement can change as other inter-related features change. For flood mitigation, woodland strips are optimally placed where they most ameliorate the effects of up-slope flood generating areas; if the flood-generating properties of these upslope areas are changed (e.g., through change in land management or addition or removal of other ameliorating features) then the optimal solution is expected to be different. Scenario exploration removing features can be used to identify those which provide large benefits to the landscape, and hence are worthy of protection.

### 3.3. Erosion/sediment delivery risk layers

Fig. 4a and b shows areas of land in the Pontbren catchment that are potentially at risk of severe soil erosion. Areas of "opportunity for change" have CTI values (see Section 2.3 for definition)

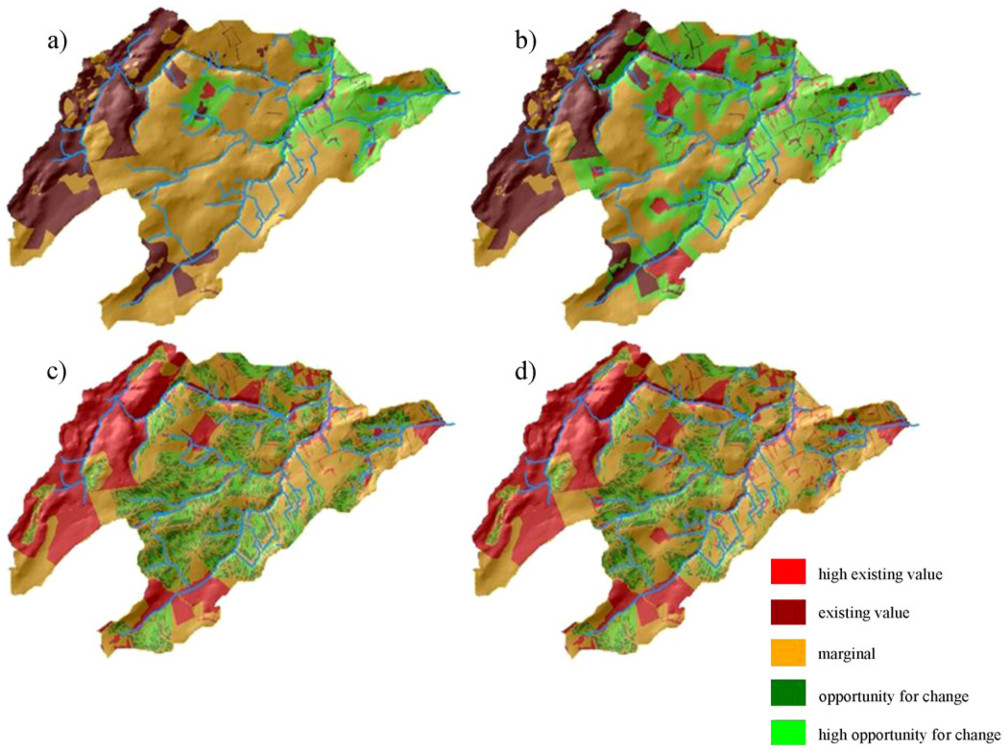


**Fig. 3.** Polyscape habitat connectivity and flood risk layers. (a) The habitat connectivity layer using vegetation survey data collected ca. 1990 while (b) the same layer using an updated vegetation dataset corrected for recent planting. Similarly, (c) the flood mitigation layer for broadleaved woodland using the original survey data, while (d) gives the same layer using the updated data.

**Table 1**
Percentage areas of catchment covered by broadleaf habitat, covered by other "priority" habitats, of negligible biodiversity value but accessible to broadleaf focal species, and of negligible biodiversity value and not accessible to broadleaf focal species, using two scenarios. The first scenario uses vegetation data ca. 1990 and the second vegetation as of 2007 (after a concerted programme of broadleaved woodland planting and pond creation).

| | Broadleaf habitat (%) | Other priority habitat (%) | Other accessible area to broadleaf focal species (%) | Area non-accessible to broadleaf habitat focal species (%) |
|---|---|---|---|---|
| Ca. 1990: pre-tree planting | 3.0 | 21.8 | 15.0 | 60.2 |
| Ca. 2007: post-tree planting | 9.8 | 21.5 | 36.7 | 32.0 |

**Table 2**
Changing proportions of flood-mitigating (permeable high storage) land, flood mitigated land (low permeability or low storage land intercepted by flood mitigating land before reaching watercourses) and non-mitigated land (low permeability or low storage land not intercepted by flood mitigating land enroute to watercourses) using two vegetation scenarios. The first scenario uses vegetation data ca 1990 and the second vegetation as of 2007 (after a concerted programme of broadleaved woodland planting and pond creation).

| | Flood mitigating land (%) | Mitigated flood generating land (%) | Non-mitigated flood generating land (%) |
|---|---|---|---|
| Ca. 1990: pre-tree planting | 27.2 | 31.4 | 41.4 |
| Ca. 2007: post-tree planting | 30.4 | 40.2 | 29.4 |

exceeding 10 m, while areas of "high opportunity for change" have CTI values exceeding 50 m. These thresholds were selected on the basis of empirically derived critical CTI values presented in Parker et al. (2010). Areas of land in the Pontbren catchment that would be suitable for sediment delivery mitigation efforts are identified in Fig. 4c and d. Areas of "opportunity" have CTI values that exceed 10 m and have an unmitigated flow connection to a watercourse, while areas of "high opportunity" have CTI values that exceed 50 m and have an unmitigated flow connection to a watercourse. Areas of "high existing value" provide protection by breaking connections of sediment sources to the stream and "marginal" areas are either at negligible risk of contributing substantial sediment or already benefit from features (land use and soil type) that intercept and hence limit sediment delivery.

### 3.4. Carbon layer

Despite the global attention given to carbon stocks and emissions in the last decade, collating soil and biomass carbon data was far more problematic than initially anticipated for many vegetation classes and soil types. A literature search and expert judgements eventually populated a look-up table of above ground and below ground biomass, deadwood, litter and soil carbon estimates allowing spatial mapping of carbon stocks. Where multiple studies were available, estimates varied significantly from source to source and therefore must be considered as having considerable uncertainty. In other cases, data did not appear to be available and had to be estimated from "similar" vegetation/soil types.

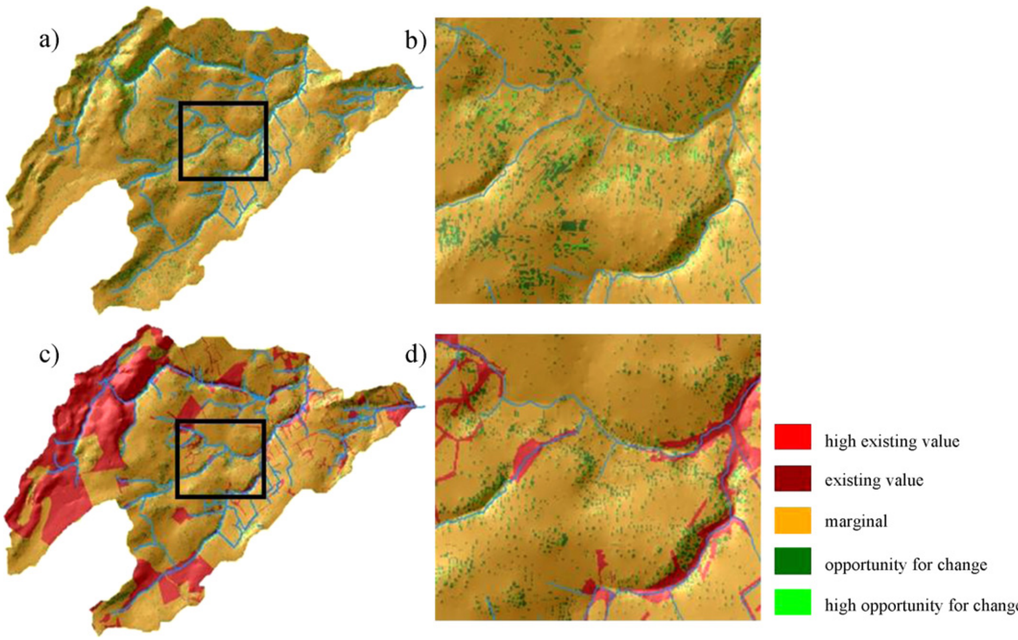


**Fig. 4.** Erosion and sediment delivery vulnerability layers. (a) The erosion vulnerability map for the catchment, (b) a close-up of a portion, (c) areas from which the stream is vulnerable to sediment delivery and (d) a close-up of those areas.

Welsh or at least UK specific data were available for many quantifications of carbon and were used where possible. UK-sourced underlying data for the maps shown here came from Adger, Brown, Shiel, and Whitby (1992), Adger and Subak (1996), Dyson et al. (2009), FRA (2010), Patenaude (2003), Patenaude et al. (2004), Smart et al. (2009) and Smith et al. (2000). Where no "similar" carbon quantifications could be found in the UK literature, numbers from the IPCC guidelines for National Greenhouse Gas Inventories (IPCC, 2006) were used. These were further supplemented with data from Conkling, Hoover, Smith, and Palmer (2002) and Cacador, Costa, and Vale (2004) where the IPCC inventories were deficient (e.g., saltmarsh information).

Polyscape asks the user to input threshold values for identifying opportunities for additional sequestration and/or areas for preservation. There are no existing guidelines for this in the UK so the thresholds were based on the range of the data available in the catchment. Stocks above 500 kg/ha are considered of very high value, stocks between 200 and 500 kg/ha of somewhat high value, stocks between 150 and 200 of moderate value, stocks between 80 and 150 as low value and less than 80 kg/ha as very low existing value (providing high opportunity for sequestration).

Fig. 5a considers current carbon stocks and Fig. 5b considers whether, given the current land use and soil combination, carbon is being sequestered or emitted (gained or lost by the terrestrial pool). For example, one of the highlighted areas in Fig. 5 is a peat soil under forestry. This is likely to have a fairly high carbon stock, hence Fig. 5a shows it as worthy of protection. Conversely, Fig. 5b implies that it is not currently being protected appropriately from the point of view of this particular service – the stock is likely to be reducing. Further, this implies that this part of the catchment may be a carbon source. A second example is provided by the blanket bog identified in Fig. 5. This has a very high current carbon stock, and so Fig. 5a flags at as being of high priority for protection. Its current land management regime (Fig. 5b) suggests the carbon stock is persisting (neither increasing nor decreasing). Together, the two layers indicate this blanket bog area is under a near-optimal management as well as having near-optimal carbon stocks. These two valuation layers provide very different but complementary pictures of the carbon situation in Pontbren.

The data deficiencies in carbon stock values, along with deficiencies in the land use and soil data, must not be ignored when interpreting the carbon opportunity maps presented here. However, they do at least provide an indicative snapshot of carbon opportunities and existing provision in the Pontbren landscape.

### 3.5. Agricultural productivity layer

Pontbren output is based on current land management regime, slope, susceptibility to waterlogging and aspect. As soil fertility information was not available with the soil dataset used in the Pontbren implementation, the agricultural productivity valuations ignore this.

Fig. 6a values the land independently from its current land use; bright red indicates sites with very high potential productivity (e.g., flat and well-drained land); dark red denotes land with moderate potential; orange suggests marginal land (e.g., moderately sloping so difficult to manage with normal machinery); green land is deemed to have little or no agricultural value (e.g., steep and/or normally waterlogged). Fig. 6b and c provides variations of the complementary valuation; orange indicates the land appears to be being farmed at a level appropriate to its potential; e.g., flat, well-drained land is under intensive agriculture while hilly terrain might be under rough grazing. Red indicates over-utilisation while green indicates under-utilisation of the potential of the land. The five-way colour map in Fig. 6b provides more detail, but can be time-consuming to interpret. The three-colour map in Fig. 6c is therefore provided to facilitate an overview of the utilisation situation. Fig. 6d is a food security map; with bright red indicating very high food production (e.g., arable crops), dark red fairly high production (e.g., livestock grazing), orange some food benefit (e.g., hunting) and green no food. Although this fourth map is arguably of least interest in nationally and globally well-connected catchments such as Pontbren, it does allow consideration of the sustainability of a community if transport or trading links are interrupted and could be particularly relevant for applications in isolated or war-torn regions.

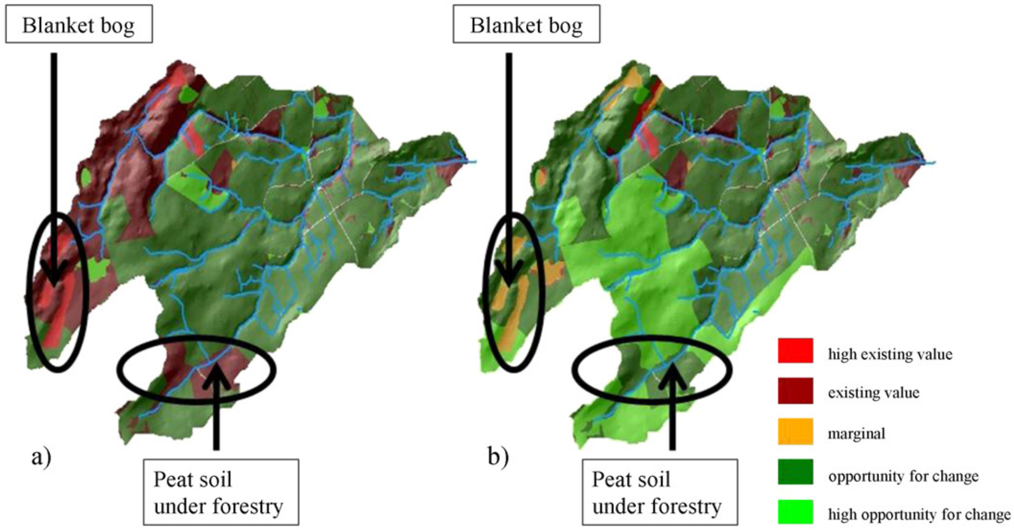


**Fig. 5.** Carbon tool outputs considering (a) current carbon stocks and (b) steady-state carbon sequestration and/or emission versus sequestration rates.

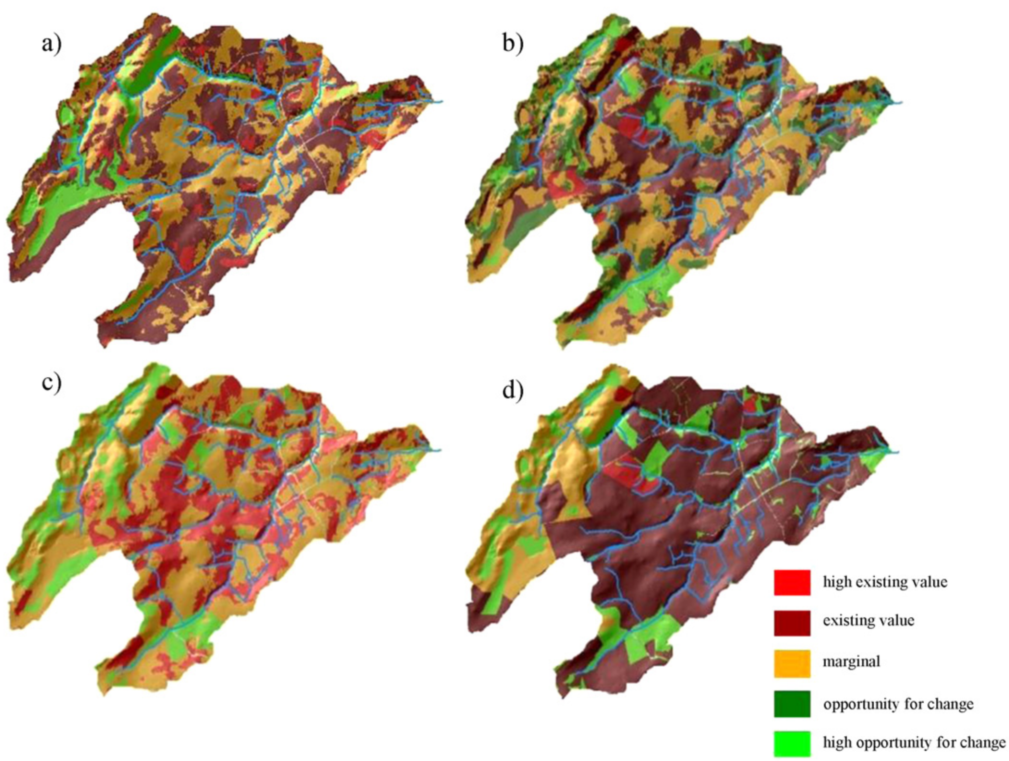


**Fig. 6.** Agricultural valuations. (a) The categorization of the landscape into agricultural productivity categories irrespective of current land use; (b) examines whether land is being under or over utilised according to the default 5-way categorization system, (c) considers the same using a 3-way categorization system, and (d) examines food security.

**Table 3**
Changing pictures of priorities for targeting change or preservation as services under consideration change. Land under Category 1 is providing benefit to all services under its existing management regime, Category 2 is providing benefit to some services and no negative impacts under its existing regime; Category 3 is EITHER land providing negligible current provision but also with negligible opportunity to enhance this provision OR its current management regime is positive for some services and negative for others. Category 4 land indicates opportunity to improve some services without degradation in any others, and Category 5 land indicates opportunity to improve all services.

| Services being examined | Category 1 | Category 2 | Category 3 | Category 4 | Category 5 |
|---|---|---|---|---|---|
| Two services: flood mitigation and habitat | 27.7 | 4.7 | 20.5 | 40.5 | 6.6 |
| Two services: agriculture and habitat | 13.1 | 38.1 | 36.5 | 11.7 | 0.6 |
| Two services: productivity and flood mitigation | 14.3 | 26.5 | 39.3 | 18.0 | 1.9 |
| All three services: productivity, flood mitigation and habitat | 12.5 | 11.6 | 71.3 | 4.4 | 0.2 |

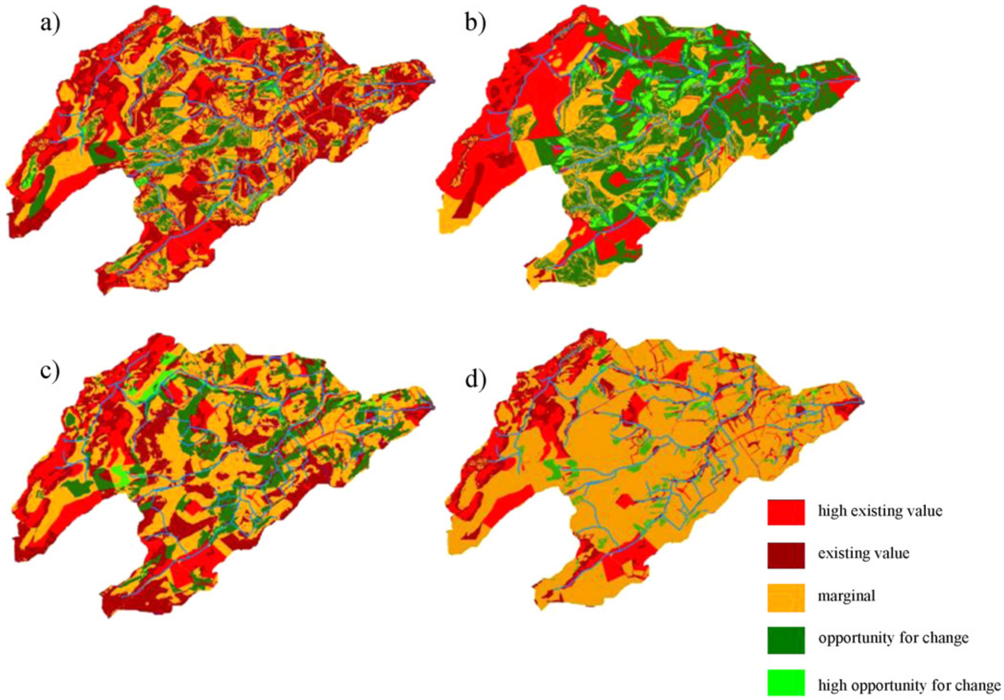


**Fig. 7.** Polyscape trade-off layers, demonstrating how landscape decisions change when two or more criteria are traded off against each other. (a) Flood mitigation versus agricultural productivity services, (b) flood mitigation versus broadleaved woodland habitat services, (c) agricultural productivity versus broadleaved woodland habitat services and (d) trade-offs between three services: flood mitigation, agricultural and broadleaved woodland habitat services.

### *3.6. Synergies and trade-offs layers*

By running those layers of interest through the trade-off algorithms, it is possible to identify areas where interventions provide multiple benefits and those where intervention is undesirable due to the existing agricultural or ecological value. For example, consider three of the services provided by the current (post-tree planting) Pontbren landscape: agricultural productivity, habitat provision, and flood risk mitigation opportunities. Fig. 7 identifies locations in space where synergies, deteriorated services, or trade-offs between services would occur if planting further broadleaved woodland, while Table 3 summarises the percentages of land where various combinations of negative or positive benefits from planting would occur.

There are small areas where tree planting meets all criteria (shown as light green); a high proportion of areas where the effect on a single service is good and on other services is neutral (dark green); a moderate number of areas where new broadleaved woodland would impact negatively on one (dark red) or several (bright red) services while having no or negligible positive benefits on other services, and large areas are dominated by trade-offs amongst ecosystem services, where one or more can benefit but only to significant detriment of one or more others, i.e., requiring large incentives to promote, or have low impact for all criteria (shown as orange). Where service provisions are relatively independent of each other in function (as in this example), we find increasing the number of services under consideration generally greatly increases the amount of land where trade-offs in service provision exist. However, where services are more interlinked, as for example with flood mitigation, erosion and carbon sequestration, more synergies in service provision exist and hence large proportions of land provide multiple existing services or conversely provide an opportunity to increase provision of multiple services.

## 4. Discussion and conclusions

Polyscape is designed to be appropriate for supporting decisions from sub-field scale to ca 10,000 $km^2$ catchment scale (the upper limit is not fundamental; it reflects the point at which personal computers struggle to run algorithms "in real time" in exploration of scenarios with stakeholders). The ability to examine sub-field scale impacts is critical for land owners, as this is the scale at which they often implement interventions, and the ability to then observe the cumulative effect of multiple changes at this scale at catchment scale provides a means for policy-makers to interrogate the potential of farm-level changes.

Polyscape has a number of other features and capabilities not contained in any other ecosystem service support framework in current circulation. It is designed for transparency of communication and to force stakeholders rather than modellers to balance the respective values of differing ecosystem services. Despite the admittedly significant simplifications in the algorithms presented in this paper, local stakeholders (farmers, environmental managers and policy makes) have understood the output and engaged in developing and using the tool. Incorporation of *interactive land owner preferences* (through parameter, data and condition editing capabilities) has been important to ground-truth land cover data and capture and engage local stakeholders. We have found the addition of parameters that could be changed, and discussed, was vital to the engagement and mutual learning process.

Ground-testing of Polyscape predictions suggests the algorithms are appropriate where data are of a sufficient quality – *all* identified issues to date have been to do with inconsistencies and/or artefacts in data. Local stakeholders have otherwise agreed with the categorisations produced (flood prone land, agriculturally productive land, etc.). We acknowledge there are many issues with regionalisation. We have applied these algorithms with significant success in multiple temperate to sub-temperate regions within

Wales, England, New Zealand, Greece, and Kenya. We acknowledge this does not demonstrate global applicability and wish to explore extensions in different climatic regimes as well as incorporating other services into Polyscape. In the near future, water quality algorithms and algorithms exploring visual, cultural and tourism amenity are high on our priority list. We also intend to include the effect of non-negotiable areas, i.e., areas which under any but the most extreme circumstances would be considered inviolable due to legal restrictions or on cultural or religious grounds (e.g., sites of special scientific significance, culturally important buildings or natural features, etc.). The exploration of uncertainty is also key to any decision making process but fraught with difficulty due to the lack of work examining *spatial* uncertainty (MacEachren, 1992; Stein, Hamm, & Qinghua, 2009).

Multiple augmentations to the algorithms we have presented are possible. For example, the flood mitigation algorithm attempts to "break up" connectivity of low-permeability flood-generating land through provision of buffers and barriers. A modification that considers removing barriers to areas where water storage is beneficial is an obvious step forward. The flood and erosion algorithms currently focus on waterways only. However, roads and other infrastructure also suffer from being washed out and/or eroded and algorithms are currently being developed to identify roads and other features at risk of being damaged by water or eroded land slips. The farm productivity impact layer could be modified to account for ease of access to land and economic drivers; the carbon layer to consider impacts of animal stocks and changes in climatic drivers; the habitat connectivity layer to consider the value of fragmentation to respect predator-vulnerable endangered species. These and many other extensions are key to moving towards a globally applicable and versatile tool.

Despite the limitations imposed by inherent inaccuracies within national data sets, Polyscape has met with considerable success for the following reasons:

(1) the simplicity of the algorithms, pragmatic rule base and openness with assumptions has readily engaged stakeholders;
(2) the two-way information exchange has allowed local stakeholder requirements and knowledge to be fully incorporated in the decision making process; and
(3) the non-prescriptive, explorative nature of Polyscape, which highlights multiple options for change.

In conclusion, Polyscape integrates multiple perspectives, multiple sources of information, and multiple services in an objective and non-judgemental manner to address the environmental consequences of land management decisions. We hope it is a firm step in the direction of a holistic approach to rural land use sustainability.

## Availability and further information

As a flexible and interdisciplinary framework, Polyscape is now spawning multiple strands of development. Information, updates and contact details for those strands we are aware of will be maintained in the near to medium term at http://www.polyscape.org/updates and http://www.polyscape.org/contact. Availability and contact details for software implementing the algorithms described in this paper and future extensions will be maintained at http://www.polyscape.org/software. The original main developers of the framework concepts (Bethanna Jackson and Tim Pagella) can also be contacted at bethanna.jackson@vuw.ac.nz and t.pagella@bangor.ac.uk.

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